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OPERATION OF THE EUROPEAN XFEL TOWARDS THE MAXIMUM ENERGY

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Abstract

After the initial commissioning of the available 25 radio frequency (RF) stations of the European XFEL (RF gun, A1, AH1 and stations A2 through A23) a maximum electron beam energy of 14.5 GeV was achieved, 3 GeV short of the design energy of 17.5 GeV. In order to tackle this problem, the Maximum Gradient Task Force (MGTF) was formed. In the scope of the work of the MGTF, RF stations A6 through A25 (linac L3) were systematically investigated and voltage-limiting factors were identified and improved. As a result, the design electron beam energy was exceeded at 17.6 GeV on 18th of June 2018. Beside this an overview over the regular RF operation at the European XFEL is given.

INTRODUCTION

The European X-ray Free-Electron Laser (XFEL) [1] is operated at the Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany. Currently up to 6000 coherent laser pulses per second with a duration of less than 100 fs and with a wavelength down to 0.62 Å are delivered to the experiments. In future the number of pulses will increase to the design value of 27000 per second. For the production of these laser pulses, electrons have to be accelerated using a 1.5 km long accelerator based on superconducting radio frequency (RF) technology. In order to provide a highly reproducible and stable electron beam, a precise regulation of the RF fields within the superconducting cavities (SCC) is required. The hardware standard in which the low-level radio-frequency (LLRF) systems are realized is Micro Telecommunications Computing Architecture (MicroTCA.4) [2].

Figure 1 shows a schematic of the facility. It is divided into various subsections, including the ones for electron beam acceleration: the injector I1 and the linacs L1, L2 and L3. The sections L1 and L2 are part of the bunch compression sections and are operated at electron beam energies of 700 MeV and 2.4 GeV, respectively. The additional energy gain up to the design energy of 17.5 GeV [1] is realized in L3. The RF stations in sections L1 to L3 have a master-slave configuration. For further information on the system architecture see [3, 4]. As high power RF sources 10 MW multi–beam klystrons are used. The electron bunches are distributed [5] to the beam dump TLD, to the north branch including undulator sections SASE1, SASE3 and the beam dump T4D as well as to the south branch including undulator section SASE2 and the beam dump T5D.

MAXIMUM ENERGY REACH

Initial Situation

The maximum design electron beam energy of the European XFEL is 17.5 GeV [1]. After early commissioning of the RF stations up to A23, a maximum energy of 14.5 GeV was achieved. Results from the Accelerator Module Test Facility (AMTF) [6, 7] tests and subsequent waveguide system tailoring predicted a theoretical maximum energy of 17.9 GeV. Figure 2 shows the corresponding VS voltages per RF station in grey. However, in reality, measurement and installation errors can only reduce this value. Furthermore 10 cavities have been detuned after the modules were installed in the tunnel due to high field emission, due to coupler issues, etc. [8]. Nevertheless, it was expected that sufficient margin still remained in the stations to be able to achieve the required design energy. To achieve this, a careful and systematic set up and investigation of each individual station was required.

Mitigation Strategy

In order to reach and exceed the design energy of 17.5 GeV a team of RF station sub-system experts (e.g. for cavities, couplers, klystrons, LLRF, waveguides, etc.) was assembled, the Maximum Gradient Task Force (MGTF). It performed investigations of individual RF stations on a weekly basis. For the investigations extensive use of the very flexible timing system was made. It generates an

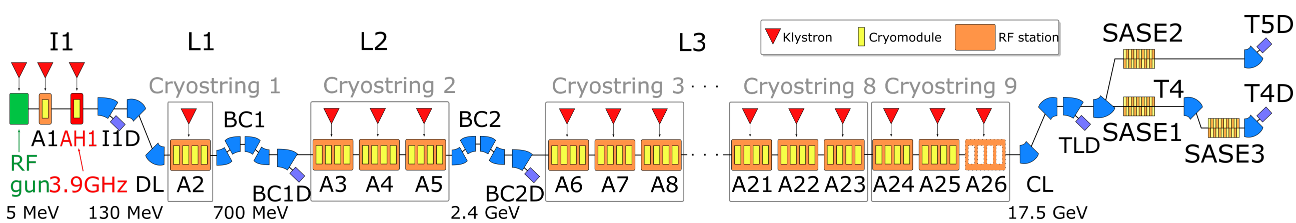

Figure 1: Schematic of the RF stations, the cryostrings and the accelerator sections of the European XFEL.

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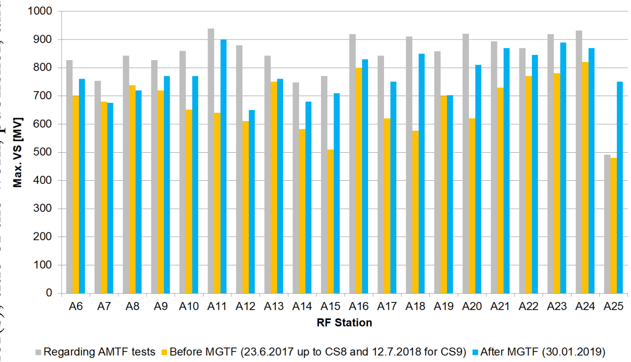

Figure 2: Maximum VS gradients of L3: estimated from AMTF tests (grey), measured at XFEL before the MGTF efforts up to A23 on the 23rd of June 2017 and up to A25 on the 12th of July 2018 (yellow) as well as at XFEL after the MGTF efforts on the 30th of January 2019 (blue).

individual trigger for every RF station. By this the timing of an arbitrary subset of RF stations can be shifted in respect to the trigger of the electron beam. This allowed to study the RF stations in parallel to regular beam operation and even during user runs. In total 40 investigations were conducted. All investigations were performed following the same checklist in order to guarantee an unified testing procedure. Based on the findings, solutions for the maximum possible vector sum (VS) voltage were determined and implemented. All findings were documented in unified RF station reports.

Results

Two categories of limitations were found, namely insurmountable and surmountable limits. The insurmountable limits were cavity quenching, reaching the field emission limit of 500 µSv/h of neutrons and missing piezo operation. The quench gradients were determined by the evaluation of the beam-based calibrated cavity probe signals. The radiation level was measured by a robot (MARWIN [9]) equipped with a radiation detector (PANDORA [10]) moving along the RF stations. The piezo operation was not possible due to missing piezo driver electronics at the time of the investigations.

The surmountable limits were waveguide sparking and too low klystron power. The waveguide sections, which showed sparking, were replaced. It was confirmed afterwards that waveguide distribution systems can sustain the power levels required for maximum for maximum VS voltages. If the klystron power was insufficient, its high voltage was increased. It turned out this was only an issue of the initial setup. The klystrons per se were never the limiting factor.

As a result of these studies, 12 cavities have been detuned in order to maximize the available VS voltages of the RF stations. In total 22 cavities are currently detuned. The improvements of the maximum RF station VS voltages are shown by the blue bars in Figure 2. An average of 93.6% of the AMTF estimations have been reached. Due to the work of the MGTF, the energy gain in L3 was increased by 1.9 GeV, which corresponds to about 2.4 L3 RF stations. Figure 3 shows the estimated maximum possible electron beam energy after every MGTF investigation (assuming 2.4 GeV after L2). On the 12th of July 2018, after basic commissioning of the last two RF stations A24 and A25, the design energy of 17.5 GeV was exceeded by 100 MeV. In order to make this possible, the energy at L2 was increased by 200 MeV to 2.6 GeV. In the following days cavities of A25 were conditioned, allowing an increase of the maximum VS voltage of that station by about 100 MV. On the 18th of July 2018 the design energy of 17.5 GeV was again exceeded by 100 MeV, this time while keeping L2 at the design energy of 2.4 GeV. Figure 4 shows a screen shot of the beam line overview panel during this run. This was a major milestone in the commissioning of the European XFEL.

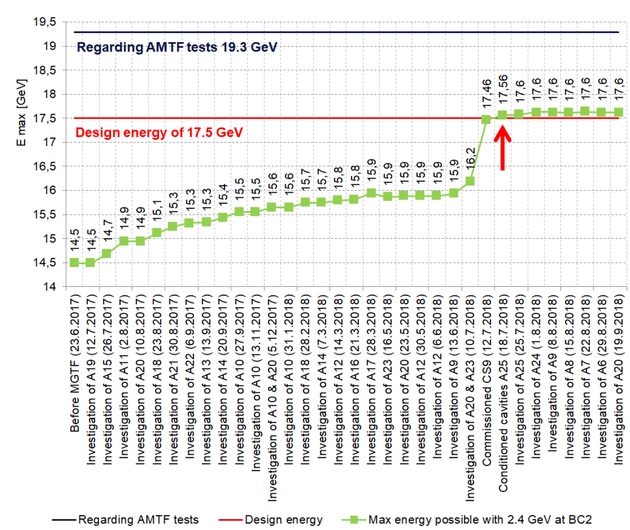

Figure 3: Maximum electron energy over MGTF investigations (green), 17.5 GeV design electron energy (red) and the theoretical AMTF-based upper limit (dark blue).

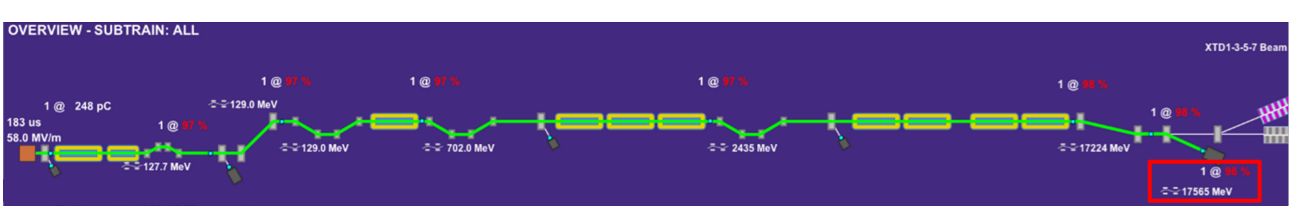

Figure 4: Screen shot of the overview panel of the beam line from the RF gun to the TLD during the first reach of the 17.5 GeV after L3 while keeping the design energy of 2.4 GeV after L2 on the 18th of July 2018.

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RF OPERATION PERFORMANCE

The requirements for the in-loop amplitude and phase stability over the flattop is 0.01% and 0.01°, respectively [1]. Figure 5 shows the amplitude and phase stability reached at the XTL RF stations. The achieved performance in amplitude and phase is up to a factor of 2 more stable than required. The differences in stability from station to station result from differences in the detuning of the cavities. The presented data was taken during nominal operation with beam (600 bunches, 0.25 nC, 1.125 MHz spacing). Algorithms such as the multiple input multiple output-based feedback controller [4], the learning feedforward [11] and the beam loading compensation [12] were active. The required level of RF amplitude and phase stability is continuously and reliably met since the commissioning in 2017.

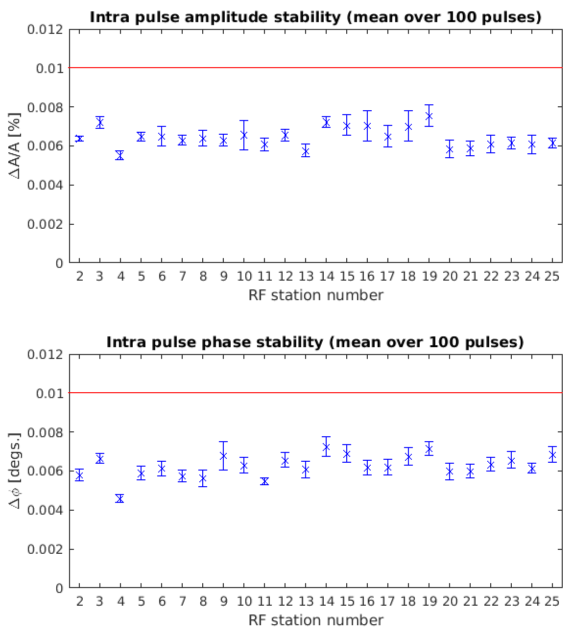

Figure 5: In–loop intra–pulse amplitude (top) and phase (bottom) stability of the XTL RF stations averaged over 1000 pulses as of 30th of May 2019. The red line indicates the required stability level.

SUMMARY AND OUTLOOK

In mid 2017 the maximum possible electron energy of 14.5 GeV was much lower than expected. As a reaction to this the MGTF was founded. After about one year of work and 40 investigations of all 20 L3 RF stations the design electron energy of 17.5 GeV was reached and exceeded by 100 MeV on the 18th of July 2018, while keeping the design energy of 2.4 GeV at the bunch compressor 2. This was a major milestone during the commissioning of the European XFEL. After the MGTF studies the piezo driver electronics have been installed. Their commissioning is expected to be finished mid 2019. After this two RF stations, which were limited by the missing piezo operation, have to be investigated again. Hardware modifications such waveguide distribution system optimization in order to retune cavities, which have been detuned during the MGTF studies, are considered. The main goal of current investigations has shifted from reaching maximum electron energy to operating the RF stations reliably at their established limits.

The amplitude and phase regulation performance of the LLRF systems meet reliably the requirements since the conclusion of the commissioning in 2017 with plenty of head room. The commissioning of the beam loading compensation ensures this also for quickly changing bunch train lengths.

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